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Effects of Radiobiological Uncertainty on Shield Design for a 60-Day Lunar Mission

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Abstract

Some consequences of uncertainties in radiobiological risk due to galactic cosmic ray exposure are analyzed to determine their effect on engineering designs for a first lunar outpost—a 60-day lunar mission. Quantitative estimates of shield mass requirements as a function of a radiobiological uncertainty factor are given for a simplified vehicle structure. The additional shield mass required for compensation is calculated as a function of the uncertainty in galactic cosmic ray exposure, and this mass is found to be as large as a factor of 3 for a lunar transfer vehicle. The additional cost resulting from this mass is also calculated. These cost estimates are then used to exemplify the cost-effectiveness of research.

Introduction

Exposure to radiation in human space exploration is an unavoidable occupational hazard. However, if the probability that crew members will experience harmful effects from radiation can be adequately reduced, the risks may be judged acceptable when mission objectives and other mission risks are considered. Radiation exposure risks are characterized as stochastic and nonstochastic. The main stochastic effect is cancer induction, and the main nonstochastic effects are early prodromal response, temporary sterility, and lens opacity.

In the United States, the current criteria for defining acceptable risk levels are those recommended by the National Council on Radiation Protection and Measurements (NCRP). The criteria are based on an analysis of annual fatality rates from accidents in different occupations. On this basis, risk of stochastic effects is defined in terms of the increase in lifetime probability, above and beyond the natural incidence, that the radiation exposure will result in fatal cancer. According to this definition, an acceptable risk level for this excess probability is 3 percent or less (ref. 1). Such a risk is considered acceptable for routine space operations in low Earth orbit. Similarly, the NCRP has also established dose limits to reduce the risk of nonstochastic effects (ref. 1).

For low Earth orbit (LEO), the predominant radiation exposure is from electrons and protons. For this radiation, extrapolations based on existing radiobiological data may be adequate for establishing exposure limits. These limits (table 1) are given in terms of common radiation protection quantities, such as the dose D , the dose equivalent H , and the quality factor Q relating D to H :

$$H = QD \quad (1)$$

Table I. Exposure Limits for LEO Operations

Exposure time	Exposure limits, Sv		
	Blood-forming organs	Eye	Skin
30 days	.25	1	1.5
Annual	.50	2	3.0
Career	^a [2 + 0.075 (age - T_o)]	4	6.0

^aAverage career dose-equivalent limit for both male ($T_o = 30$) and female ($T_o = 38$) astronauts for a 3-percent increase of cancer risk (ref. 1).

In equation (1), the quality factor is a function of the linear energy transfer (LET) of the radiation. The exact functional form is prescribed in the process of establishing radiation guidelines that make Q a legislated quantity rather than the result of a measurement. However, the dependence of Q on LET, $Q(L)$, is intended to reflect a judgment related to the dependence of relative biological effectiveness (RBE) on LET. For a radiation field with a distribution of LET values, the use of the following average quality factor (ref. 1) is required:

$$\bar{Q} = \frac{1}{D} \int Q(L) \frac{dD}{dL} dL \quad (2)$$

where $\frac{dD}{dL}$ is the dose contribution per unit LET interval.

For galactic cosmic rays (GCR's) and, in particular, for the highly charged, energetic nuclei (HZE particles) that constitute their biologically most significant components, these quantities may no longer provide an adequate description of the radiation risk (ref. 1). Evidence that extrapolations from existing radiobiological data are not adequate has been provided by the measurement of sister chromatid exchanges in resting human lymphocytes irradiated

with ^{238}Pu α -particles (ref. 2), by the observation of abnormalities in stem cell colonies surviving similar α -particle irradiation (ref. 3), and by the partial disintegration of chromosomes after irradiation with high-energy heavy ion beams to simulate space radiation (ref. 4). In these examples, the notion of a quality factor related to RBE becomes meaningless. That is, at doses comparable with those delivered by one or a few particles and for radiation effects that are not manifest for low LET radiation (e.g., X-rays), the RBE becomes infinite. Thus, new methods to predict the risk resulting from exposure to GCR radiation must be developed.

In addition to the problems posed by radiation effects that are not observable at reference doses of low LET radiation, risk estimates are uncertain, even for known radiation effects. In the United States, the NASA Space Radiation Health Program has been established to sponsor research intended to further "the scientific basis for the radiation protection of humans engaged in the exploration of space" (ref. 5). A major program objective is to reduce the uncertainty in the prediction of radiation risk so that it is within a factor of 2 (50- to 200-percent range) by 1997 and within a factor of 1.25 (± 25 percent) by 2010, as shown in figure 1.

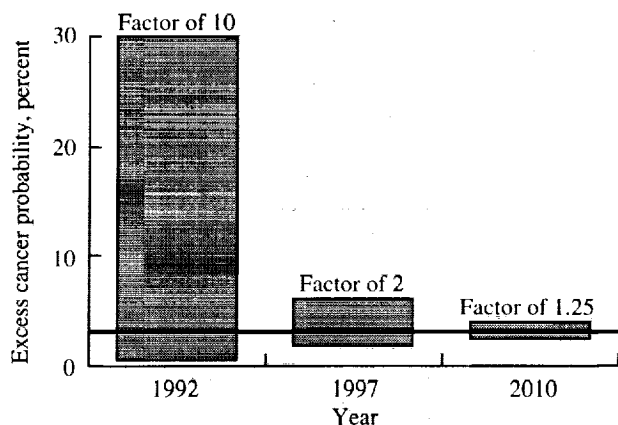


Figure 1. NASA Space Radiation Health Program estimates for current and projected risk uncertainties.

The current uncertainty in risk predictions is estimated to be as large as an order of magnitude (10- to 1000-percent range). This value is no more than an educated guess obtained with the assumption that the uncertainty of a factor of 10 is the uncertainty in the prediction of shielding effectiveness (a factor of 2 to 3) combined with the uncertainty in predicting biological response to HZE particles (a factor of 4 to 5).

Engineers and mission planners must compensate for these uncertainties to ensure that risk limits are not exceeded. Depending on policies and engineering judgment, the compensation required may be 1, 2, or more standard deviations (with a Gaussian distribution assumed for the uncertainties). For example, if predictions of risk are considered to be accurate only within an order of magnitude (factor of 10), the shielding of a spacecraft required to remain below a 3-percent excess cancer risk may, in reality, be designed for a 30-percent excess cancer risk because these uncertainties are not reflected in the shield design. Thus, this design is clearly not acceptable. In view of such large uncertainties, the shield mass should be greatly increased to ensure that the excess cancer risks do not exceed 3 percent.

The compensation required for uncertainty can significantly increase costs. If the shielding thickness of a lunar or Martian habitat has to be increased by a factor of 2, the total shield volume (mass) would increase by more than a factor of 2. As the volume increases, the time necessary for a constant work force to assemble the habitat increases; increasing the work force requires transporting more mass to orbit or increasing the number of launches. The assembly time is mostly extravehicular activity (EVA) time, and the Shuttle cannot presently support extensive EVA. Time is also quantized. Thus, the duration of one mission is expected to be 30 to 60 days. If habitat assembly extends beyond one mission duration, the number of launches doubles. If habitat assembly extends beyond two mission durations, the number of launches triples. Faster assembly of the habitat requires more machinery. Thus, the cost of machinery development, testing, and deployment must be added to the cost of launching the machinery mass. Figure 2 shows some of these relationships.

Another example of the complex effect of increasing shielding to account for uncertainties in risk

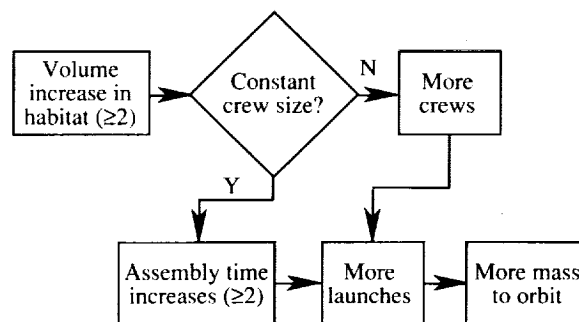


Figure 2. Logic diagram showing effects of increased shielding on launch requirements.

prediction is shown in figure 3, which is a schematic view of a typical solar energetic particle (SEP) event. The X-rays arrive at the lunar surface within 9 minutes of the start of the event and can be used as a warning signal to crews. Significant particle fluxes would begin to be experienced ΔT_1 minutes (or hours) later and would rapidly increase until, at a time ΔT_2 after the initial warning, the radiation levels inside a shielded rover vehicle on the lunar surface would exceed allowed limits. Before this time, the crew must find a storm shelter or return to the safety of the shielded base.

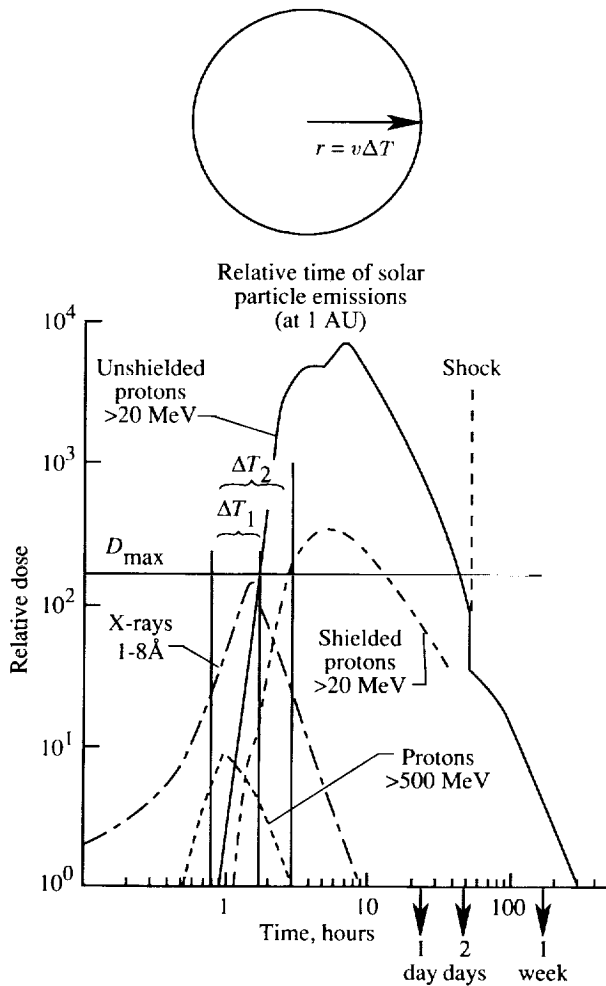


Figure 3. Limits on exploration range due to possible SEP events. Area = $\pi v^2(\Delta T)^2$; v depends on shielding and determines fuel requirements; ΔT depends on shielding and forecasting ability.

The maximum distance that a lunar rover vehicle can be allowed to travel away from a safe location is given by $v\Delta T$, where v is the velocity of the rover. This distance gives the maximum area that can be

explored in one sortie, $A_{max} = \pi v^2(\Delta T)^2$. Thus, at constant velocity, the sortie range is determined by the warning time and by the rover speed. Higher rover speed may require more fuel, more batteries, or larger engines, and it may also result in less vehicle reliability and, hence, more spare parts or backup vehicles. All of these requirements necessitate more mass lifted from Earth. Increasing the rover shielding to extend sortie time may reduce the speed and may result in similar increased mass requirements. Establishing shielded refuges to increase the surface range requires an increase in construction time and may lead to supply mission restrictions that are quantized (more launches). Another alternative is to delay surface exploration until a permanently inhabited base is established.

Current estimates of exposure (ref. 6) obtained during the establishment of a permanent lunar or Martian outpost clearly show that galactic cosmic rays limit the radiation risk (including career limits for astronauts). The uncertainties previously discussed will have a large impact on mission design and trade-offs between mission design costs, which could be greatly reduced by reducing these uncertainties through further research. As beneficial as research is for missions of long duration, what are the effects of uncertainties in biological response and shielding properties on missions of shorter duration? In the following sections, this question is considered in the context of a 60-day lunar mission.

There is interest within NASA to plan a return to the Moon for a mission duration of 45 to 60 days to establish the first lunar outpost (FLO).¹ Unlike the Mars mission or permanent lunar base where exposure to HZE particles plays a dominant role, the 60-day mission has a total GCR dose of 70 mSv or less (ref. 6). The main shield design is determined for protection from a possible SEP event and not from HZE exposure. In the following sections, a simple shielding configuration is assumed, and its modification to account for the uncertainties in risk prediction is calculated to illustrate their effects on a 60-day lunar mission. The low dose due to GCR's allows for linear approximations using risk coefficients. Finally, the model is used to estimate the effects of uncertainty on mass and projected mission costs.

While the methodology is general and can be applied to other space exploration missions, the approach described in this paper allows us to estimate the effects of uncertainty in radiation risk.

¹NASA Exploration Program Office Report: *FLO Mission Overview*, May 1992.

These estimates must be incorporated into engineering designs at the earliest possible state, so that we can realistically assess the impact of radiation protection limits. The approach described here also offers some insight into the problems of extrapolating from the current radiation limits, which are valid for LEO, to obtain valid limits for exogeomagnetospheric space exploration.

Uncertainty in Risk Estimates

In the relative risk model (ref. 7), an individual's age-specific cancer risk can be written as

$$\gamma(H) \cong \gamma_0(1 + k_R H) \quad (3)$$

In this equation, the notation of reference 7 has been modified to use H (instead of d) for dose equivalent and k_R (instead of α_1) for risk coefficient, the excess risk function has been approximated as $g(\beta) \simeq 1$, and a linear dose dependence has been assumed.

From equation (3), the relative excess risk R_R can be defined as

$$R_R = \frac{\gamma(H) - \gamma_0}{\gamma_0} = k_R H \quad (4)$$

In this approximation, R_R is independent of the natural incidence of cancer, and H is the dose equivalent (in Sv). The excess risk is

$$R = \gamma_0 k_R H = kH = k(H_x + H_z) \quad (5)$$

where H_x is the component of the dose equivalent due to low LET radiation, and H_z is the dose equivalent due to the HZE component of the radiation. We make the further approximation that the uncertainties in k and H_x are negligible in comparison with the uncertainty in H_z , and from this approximation we obtain the following equation:

$$\Delta R = k \frac{\Delta H_z}{H_z} H_z \equiv kU H_z \quad (6)$$

Thus, the net effect of the uncertainty in R is an increase in the relative excess risk, which becomes

$$R + \Delta R = kH + kU H_z = kH_u \quad (7)$$

Equation (7) defines an effective dose equivalent H_u , which corresponds to the increased risk due to uncertainties. If a limit L is defined on the basis of R , then it is required that

$$R + \Delta R \leq L \quad (8)$$

A safety factor S can be defined with reference to equation (7). Let S be an upper bound on the estimated value of the uncertainty in the HZE dose equivalent $S = nU$, where $n = 1, 2, \dots$ corresponds to the number of standard deviations required to establish an acceptable safety margin. Then equation (7) becomes

$$R + \Delta R = kH + kSH_z = kH_s \quad (9)$$

where the effective dose equivalent, including the safety factor, is given by $H_s = H + SH_z$. Alternatively, the HZE component in equation (4) can be increased according to $H'_z = H_z + SH_z = (1 + S)H_z$. This formulation suggests the possibility of using the ratio between experimental values of RBE and \bar{Q} as an approximation for $1 + S$. For example, the measured RBE for life shortening in mice has been reported to be as large as 80 for fission neutrons (ref. 8), while the estimated value of \bar{Q} is at most 20. Thus, an estimate for the value of S is 3, which corresponds to an effective dose equivalent that is 300 percent greater than one obtained from currently accepted dosimetric analyses. Such a value (300 percent) may be considered reasonable from a radiobiological point of view and may not be too restrictive for a 60-day lunar mission.

Effects of Uncertainty on Shield Design

To determine the effects of uncertainty on shield design, we consider the following example. An astronaut on a 60-day lunar mission is exposed to the low-level GCR background and is subject to the possibility of a large SEP event. For this example, we consider only the shielding of the blood-forming organs (BFO's), as this exposure is closely related to overall life shortening due to neoplastic disease. Because the mission time is not yet specified, we assume the solar minimum environment (maximum exposure) prescribed by the Naval Research Laboratory Cosmic Ray Effects on Micro-Electronics (CREME) model (ref. 9). The observed SEP's vary in spectral characteristics and intensities; thus, for design considerations, we assume an SEP model consisting of the spectrum envelope that bounds the observed fluence at any observed energy. This SEP model is similar to the Viking mission design criteria,² except the envelope is now given by the February 1956, November 1960, and August 1972 events. (See fig. 4.) The differential fluence spectral envelope $\varphi(E)$ is determined

²NASA Viking Project Office Report: *Viking Project 75*, April 1972, (M75-125-2).

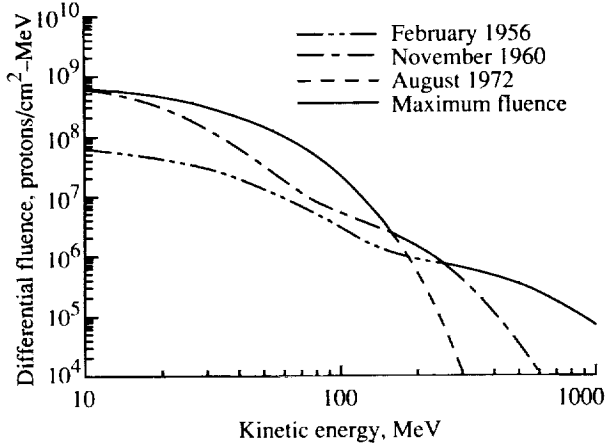


Figure 4. Estimate of maximum fluence spectrum for an SEP event.

by expressions derived from the individual flare spectral characteristics (ref. 10) and is given analytically as

$$\varphi(E) = \text{Max}(f_1, f_2, f_3) \quad (10)$$

where

$$f_1 = 6.0 \times 10^7 \exp[-(E - 10)/25] + 9.4 \times 10^5 \exp[-(E - 100)/320]$$

$$f_2 = 6.3 \times 10^8 \exp[-(E - 10)/12] + 4.9 \times 10^6 \exp[-(E - 100)/80]$$

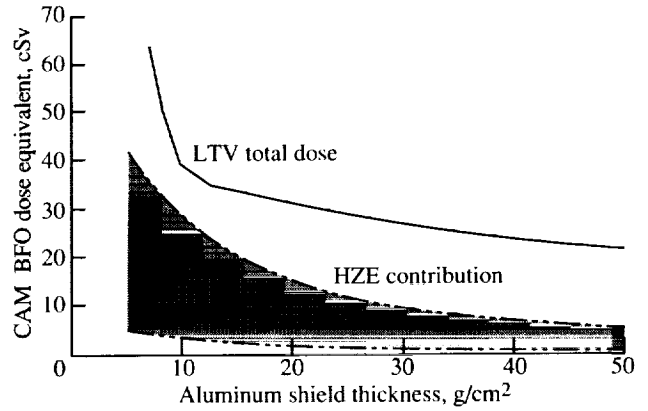
$$f_3 = 3.0 \times 10^8 \exp[-(E - 30)/26.5]$$

In equation (10), E is energy in MeV and φ is in units of protons/cm²-MeV. The f_1 , f_2 , and f_3 values represent fluences for the 1956, 1960, and 1972 flares, respectively.

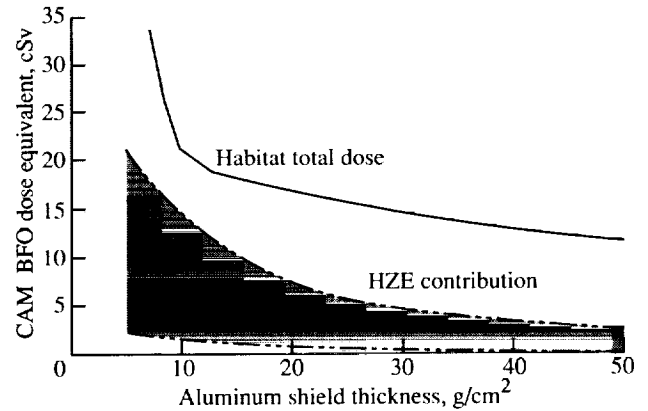
The total BFO dose equivalent as a function of shield thickness for a water-equivalent shield has been calculated with the Langley nucleon transport code BRYNTRN (ref. 11) for the flare spectrum and with the heavy ion/nucleon transport code HZETRN (ref. 12) for the GCR contribution. The assumed quality factor is the one specified by ICRP-26 (ref. 13). For simplicity, shield configurations are taken as spherical shells of constant thickness, and the dose evaluations are made at the center of the sphere. The variation of dose equivalent with shell thickness is evaluated for two configurations: (1) a complete spherical shell representing a lunar transfer vehicle (LTV) in cis-lunar space and (2) a hemispherical shell representing a habitat on the lunar surface. The dose equivalents have been computed for a mission duration of 60 days: 45 days on the lunar surface, 5 days of transit time each way, and 5 days in low Earth orbit. The dose of the LTV differs from the dose of the habitat by a factor of 2 as a result of shielding of the habitat by the moon.

The dose equivalents of the LTV and habitat are shown in figure 5 for the 60-day mission. The BFO dose equivalents have been evaluated according to the human body geometry specified in reference 14 for the NASA Computerized Anatomical Man (CAM).

Using equation (7) to specify a dose-equivalent uncertainty in the GCR dose equivalent along with the functions for the dose equivalent versus shield thickness (fig. 5), the shield thickness requirements are determined as a function of GCR dose uncertainty. These results are shown in figure 6 for the LTV and the habitat. To extend the shield thicknesses to shield mass requirements, we examine two versions of the LTV model (a totally shielded vehicle and a vehicle with a storm shelter) along with the hemispherical habitat. (See fig. 7.) For the totally shielded vehicle, we chose a minimum interior volume corresponding to reasonable astronaut performance (10.5 m³ per person from ref. 15) for a four-member crew. For the LTV with a storm shelter, the heavily shielded volume is assumed to be one-third as large as



(a) LTV total dose.



(b) Habitat total dose.

Figure 5. Estimated worst-case BFO exposure from SEP events, with spherical shell shielding thicknesses assumed.

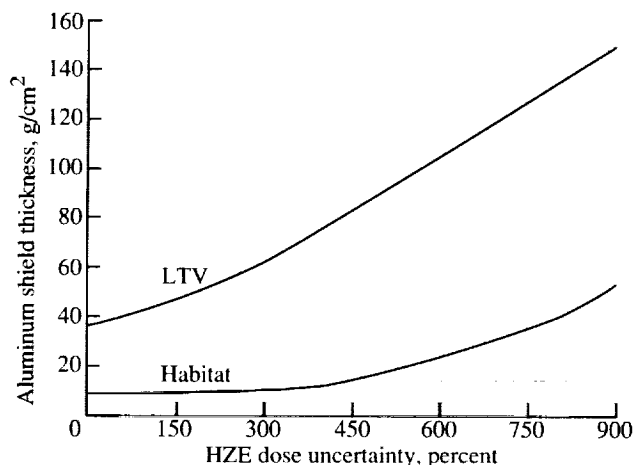


Figure 6. Shield thicknesses required to meet 30-day dose limit, with an assumed uncertainty in HZE risk coefficients.

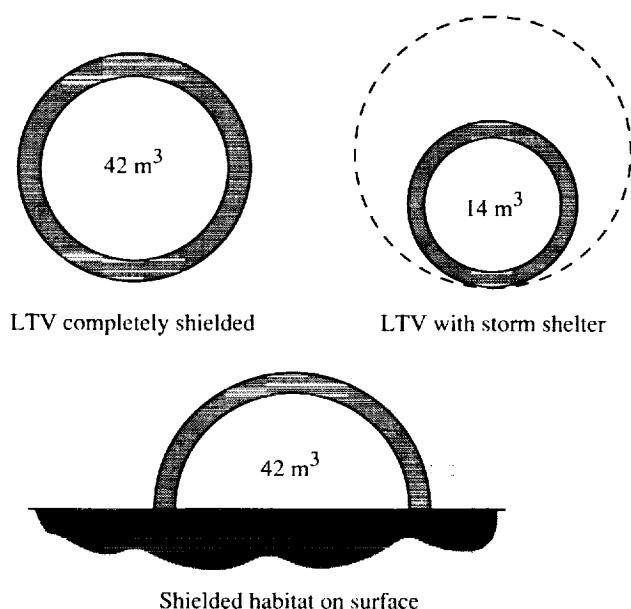


Figure 7. Lunar transfer vehicle and habitat configurations for a 60-day lunar mission.

the completely shielded vehicle. The surface habitat volume is equated to that of the totally shielded LTV. With these specified dimensions, the required masses are readily evaluated and are given in figure 8. Despite the relatively small contribution from GCR's to the total dose, substantial increases in required shield mass are necessary to offset large biological risk uncertainties for GCR's.

Accurately relating increased payload mass to elevation in mission cost for future lunar missions is very difficult. At best, rough estimates can be made on the basis of past history, which we attempted to use

in the following manner. By taking the total cost of the Apollo program (about 24 billion dollars (1970)) and the approximate payload weight of the combined eight lunar missions (about 800 000 lb from ref. 16), we calculated that the per mass cost for a lunar mission is about 30 000 dollars/lb or 66 million dollars metric ton (tonne). When this value is chosen and used in conjunction with the shield mass versus uncertainty plots shown in figure 8, the excess cost of the 60-day lunar mission due to GCR risk uncertainties is determined. (See fig. 9.) We believe these excess cost estimates are conservative in the sense that the actual missions costs would prove to be significantly higher. Figure 9 shows that an uncertainty of 300 percent adds over 1 billion dollars to the mission cost. However, an uncertainty factor reduction program is likely to cost significantly less; thus, the cost-effectiveness of research is demonstrated.

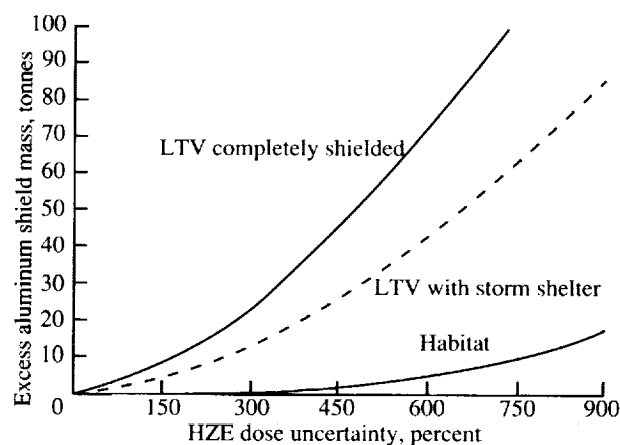


Figure 8. Estimated shield mass requirements to compensate for GCR risk uncertainties for a 60-day lunar mission.

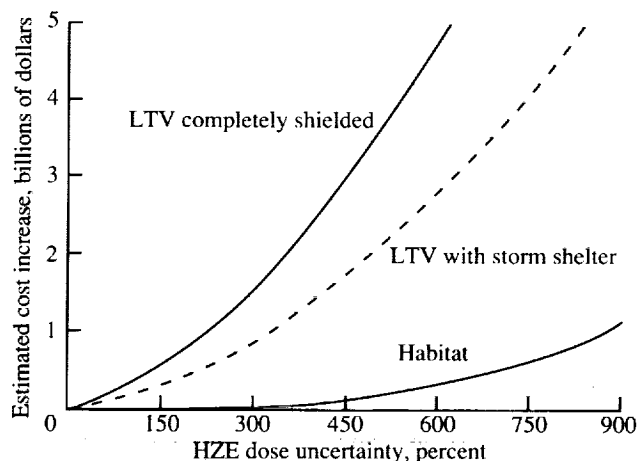


Figure 9. Estimated impact on mission cost due to GCR risk uncertainties for a 60-day lunar mission.

Concluding Remarks

The effect of risk uncertainties due to heavy ion galactic cosmic ray (GCR) exposure for relatively short-duration lunar missions has been analyzed. The results indicate that shield design and mission cost are significantly affected by these uncertainties. The analysis does not include the effect of uncertainties in shielding properties (including radiation transport), the effect of linear energy transfer dependence on risk coefficients, quadratic terms in the dose response function, dose rate considerations, and other effects that may need to be considered for special circumstances or longer duration missions; furthermore, shield requirements have been estimated for simple configurations in a severe (but not necessarily unreasonable) worst-case solar flare environment. Nevertheless, the results show that GCR risk uncertainties can dramatically impact many lunar mission parameters and that such calculations need to be incorporated into engineering design considerations at an early stage. Finally, the calculation presented here offers a new approach to understanding the cost-effectiveness of investment in research.

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December 1, 1992

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